

APPENDIX B SAFEBUCK PHASE I - DELIVERABLES

B1. SAFEBUCK PHASE 1 - BACKGROUND

Towards the end of 2002 a world-class team of experts, led by Boreas Consultants and including the Welding Institute, Cambridge University and OTM as JIP partners kicked-off the SAFEBUCK JIP. The JIP workscope included engineering studies and preparation of a **lateral buckling design guideline** by Boreas, with assessment and **testing of materials** by TWI and geotechnical **testing of pipe-soil interaction** by Cambridge University Engineering Department. OTM managed the JIP on behalf of the JIP partners.

The level of interest generated by the SAFEBUCK JIP was exceptional. BP, ConocoPhillips, ExxonMobil, Petrobras and Shell, as well as the US Government through the Minerals Management Service all participated. Installation contractors and suppliers were represented by Allseas, NKK-Mitsubishi, Technip and Tenaris.

The SAFEBUCK JIP delivered:-

- The **first ever design guideline** for on-bottom lateral buckling covering single pipe and pipe-in-pipe;
- **Unique analytical models** for laterally buckled pipeline behaviour;
- Quantification of **innovative methods** for initiating and controlling lateral buckling;
- Unique analytical equations to **quantify pipe-walking**;
- Methodologies to demonstrate the **integrity** of single pipe and pipe-in-pipe through both engineering studies and **low-cycle fatigue** testing;
- Unique **pipe-soil interaction** data for large cyclic displacements through full-scale and small-scale tests.

The additional funds raised by the high level of participation has allowed the JIP to undertake additional research into the related phenomenon of pipeline walking, as well as expanding the scope for materials testing and pipe-soil interaction tests.

Sponsor feedback on the SAFEBUCK JIP is extremely positive, with compliments on the clear guidelines and the highly readable and comprehensive reports covering the extremely challenging yet significant issues of lateral buckling and pipe walking.

B1.1. Generous Donations

The amount of project-specific data donated by participants is exceptional, and greatly contributes to the level of knowledge and understanding. Participants have also kindly donated a range of pipe for materials testing and some Gulf of Mexico soil for small-scale tests. The generous donation of pipe-soil test data from outside the JIP, in return for use of the Cambridge test facilities, has also provided invaluable pipe-soil interaction data for deepwater West African clay and has allowed additional small-scale and large-scale tests to be carried out by the JIP on this soil.

B2. SAFEBUCK JIP PHASE 1 DELIVERABLES

The key deliverable from the JIP is the **Design Guideline**; this is described in Section B2.1 The **Design Guideline** is backed up by a range of other deliverables addressing each of the activities which formed components of the JIP workscope; these are described in the subsequent sections.

B2.1. Design Guideline

The key deliverable from the JIP is the **Design Guideline**. The aim of the guideline is to facilitate the safe, economic design of pipelines that are susceptible to lateral buckling. In order to achieve these aims the integrity issues associated with lateral buckling must be considered at all phases of the pipeline design and operation. Consequently the guideline covers the following phases of the pipeline life cycle:-

- Conceptual Design;
- Detailed Design and Procurement;
- Installation Engineering;
- Operational Integrity.

The basic design approach is applicable to either conceptual or detailed design; the difference between the phases of design is simply the analysis tools employed, the availability of design data and the relevant acceptance criteria. The behaviour of PIP systems is addressed within the guideline.

The guideline provides:-

- A detailed description of the design process;
- Guidance on modelling and analysis of the lateral buckling process;
- Guidance on buckle initiation and mitigation techniques;
- Data on high temperature material properties, pipe-soil interaction and out of straightness;
- Suitable equations to address all of the key limit states.

Additional funding has allowed a design example to be prepared using the guideline to assist users in applying the recommended approach.

B2.2. State of the Art Report

This report summarises the current design methodology and project experience with the lateral buckling solution. The State of the Art report set the scene at the start of the JIP by reviewing and clarifying available data relevant to lateral buckling, which was complete in some areas and lacking in others. Further data was collected during the course of this JIP, from participant contributions and tests carried under the JIP workscope that fills many of the gaps identified in this review. For example, out of straightness (OOS) data obtained from six pipeline projects has been analysed to illustrate the level of OOS that can be anticipated in a real pipeline. The data covers two situations; the inherent OOS in a nominally straight pipeline and the OOS developed when a snake-lay strategy is adopted.

This report now presents the current understanding of lateral buckling from research and design experience and explains the approach used for the design of pipelines with lateral buckling. This explanation of design methodology forms the background to design guidance, which is the main purpose of this JIP.

B2.3. Response within a Buckled Pipeline

This report addresses the behaviour of the pipeline within a lateral buckle to ensure that the response of the buckled pipeline can be investigated in a robust manner, both in conceptual design and in detailed design, to manage the technical risk associated with lateral buckling.

Current analytical models used for concept design are based purely on elastic stress limits. In reality lateral buckling design is based on moderate plastic deformation on the first load cycle, followed by a fatigue assessment of subsequent elastic cyclic loading for the life of the line. As a consequence the existing elastic models are excessively conservative and do not address the true design limit states.

To address this problem, analytic models were developed to incorporate first load plasticity and cyclic fatigue in operation. These models were successfully validated against FE analysis and are already being used by some participants to evaluate upcoming HPHT developments.

This work also investigated the effect of modelling assumptions used in FEA for detailed design, to assess the importance of each issue and provide guidance on parameters that must be incorporated within design, to ensure a robust assessment of loads within a buckle. Issues addressed included:-

- Mathematical modelling issues;
- Strain localisation phenomena;
- Material modelling;
- Pipe-soil interaction modelling.

B2.4. Buckle Formation

This report evaluated how buckles form and outlined the key parameters that contribute to the buckling process. There are two strands to this work:-

- Buckle initiation techniques;
- Probability of buckle formation.

The design strategy will usually employ a buckle initiation technique. The available buckle initiation methods are detailed in this report, with feedback on known performance. The **snake-lay** method is becoming much better understood and a wealth of performance data has been donated to the SAFEBUCK JIP. The **distributed buoyancy** method has yet to be implemented, so performance data is not available. The **vertical upset** method has been applied to pipelines that are now operating but there is limited performance data available.

Basic probabilistic models of the buckle formation process were also developed to allow the probability of buckle formation to be quantified.

B2.5. Pipeline Walking

This report evaluates pipeline walking, which can cause global axial displacement of a whole pipeline, leading to overstressed expansion spools or jumpers, or loss of tension in a SCR. This phenomenon is normally associated with short, high temperature pipelines but it can occur on longer lines, especially where lateral buckling has occurred.

Pipeline walking occurs over a number of start-up and shutdown cycles, under the following conditions:

- Tension at the end of the flowline, associated with a steel catenary riser (SCR);
- Global seabed slope along the pipeline length;
- Thermal gradients along the pipeline during heat-up.

The study highlighted the key parameters that influence walking in each case. Analytical equations to predict the rate of walking were developed from first principals for all three conditions and validated against FE (finite element) models.

These FE models were also used to assess the significant influence on walking of variations in axial friction behaviour, which can significantly influence walking behaviour.

This study has significantly improved the understanding and prediction of pipeline walking and has highlighted certain areas where further testing and analysis is required.

B2.6. Failure Modes and Limit States

This report defines limit states that must be considered in the design process. Suitable formulations are developed for use in the design guideline. These address the key limit states within a lateral buckle, which are local buckling, fatigue and weld fracture and collapse. Local buckling failure is of most concern when a buckle is formed and generally defines the maximum plastic deformation on first load. Subsequent cyclic loading is generally in the elastic range and defines the allowable fatigue life and fracture requirements.

- Local buckling limit states are based on the significant amount of research performed by others, which is reviewed within this report, and suitable formulations are proposed.
- The fatigue limit state can be assessed using standard fatigue curves with some provisions specific to low-cycle fatigue. This approach has been confirmed through the materials testing programme.

In addition to these limit states; the pipeline material specification must be consistent with the high levels of imposed load. A limit is placed on the first load strain, to ensure that the uniform strain capacity of the material is not approached. A limit is also placed on the maximum axial stress range, to prevent cyclic plasticity; this limit considers the biaxial nature of the stresses and incorporates an allowance for the Bauschinger effect.

B2.7. Materials Testing

The fatigue performance of girth butt welds was assessed for the buckle crown which experience high levels of plastic strain followed by a relatively small number of high stress operational cycles with each shut-down and start-up. Fatigue testing concentrated on the 'low-cycle' region of the S-N fatigue design curve. 'Dog-bone' specimens were taken from full-sized girth welds and some were subjected to initial plastic pre-strain before applying cyclic fatigue at stress ranges up to 1.8 times SMYS. This involved cyclic compressive and tensile loading.

In general, the fatigue lives obtained from the endurance tests were consistent with published data for girth welds and the corresponding design classification. However low-cycle fatigue does modify fatigue performance in some cases. Testing captured the behaviour of carbon steel, manufactured by the seamless UOE and HFI methods, with single sided welds and backing-strip welds appropriate to pipe-in-pipe systems. Low-cycle fatigue tests were also carried with CRA material and in a seawater (3%NaCl) environment with cathodic protection. The influence of pre-strain on fatigue performance was also confirmed across normal to low-cycle behaviour.

Fracture and mechanical testing was performed on samples in the as-welded state, following the application of multiple strain cycles, to measure materials properties of both the parent metal and weld material at a range of operating temperatures. Suitable interpretations and modifications required to employ the BS7910 flaw assessment procedure under the conditions experienced within a lateral buckle were developed.

B2.8. Pipe-soil Interaction Testing

Pipe-soil interaction testing evaluated the large displacement, cyclic response that occurs during lateral buckling, with the associated development of soil-berms. Until this JIP, there were no data available to validate the use of force-displacement response models and the use of coulomb friction approximations is unrealistic for large lateral movements with developing soil berms.

In these tests the pipe was allowed to ride-up over, or embed and displace, the soil in its path. The response was a function of the soil properties, pipe diameter, pipe submerged weight and berm building behaviour. These tests evaluated two stages of pipe-soil interaction:

- Break-out, during buckle formation based on different levels of initial pipe embedment;
- Repeated cyclic behaviour, which is strongly influenced by the building of soil berms.

This activity included a review of existing published methodologies for small deflection lateral displacement which were found to be inaccurate with different types of clay.

Full-scale tests were carried out on a flooded soil test bed with horizontal displacement of about 8D and some assessment of berm consolidation. These tests are backed up by small-scale tests, using a drum centrifuge, to evaluate high numbers of cycles and variations in consolidation for different soils. This has allowed the SAFEBUCK JIP to evaluate typical deepwater soils from the Gulf of Mexico and West Africa to compare with the kaolin clays and West African clay used for the full-scale tests. Centrifuge testing is showing good correlation with full-scale tests, so that additional small-scale tests are planned for Phase 2.

Axial response tests on heavy and light pipes in West African clay together with axial test data for kaolin, donated to the JIP, have provided valuable information for axial response behaviour of on-bottom pipelines on a natural seabed.